

# **Communications: Mosquito Habitats, Land Use, and Malaria Risk in Belize from Satellite Imagery**

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## Abstract

Satellite imagery of northern Belize is used to examine the distribution of land use and breeding habitats of the malaria vector the *Anopheles* mosquito. A land cover classification based on multispectral SPOT and multitemporal Radarsat images identified eleven land cover classes, including agricultural, forest, and marsh types. Two of the land cover types, *Typha domingensis* marsh and flooded forest, are *Anopheles vestitipennis* larval habitats, and one, *Eleocharis* spp. marsh, is the larval habitat for *Anopheles albimanus*. Geographic Information Systems (GIS) analyses of land cover demonstrate that the amount of *Typha domingensis* in a marsh is positively correlated with the amount of agricultural land in the adjacent upland, and negatively correlated with the amount of adjacent forest. This finding is consistent with the hypothesis that nutrient (phosphorus) runoff from agricultural lands is causing an expansion of *Typha domingensis* in northern Belize. Thus, land use induced expansion of *Anopheles vestitipennis* larval habitat is potentially increasing malaria risk in Belize, and in other regions where *Anopheles vestitipennis* is a major malaria vector.

**Keywords:** mosquito, land use, malaria, Belize, marsh, satellite imagery, *Typha domingensis*, remote sensing, phosphorus

## INTRODUCTION

Natural wetlands in northern Belize provide breeding sites for a variety of *Anopheles* mosquito species that transmit malaria (Rejmankova et al. 1993, 1995, 1996a, 1998). Malaria is a persistent health problem in Belize, although control efforts in the north have prevented severe

outbreaks in recent years (Hakre 2003). Nevertheless, there is a growing concern that changing land use and demographics in the north may increase malaria risks.

Freshwater wetlands in northern Belize include a variety of marsh and forested types. The marshes of northern Belize have been studied extensively (Rejmankova et al. 1993, 1995, 1996b), and three broad types are identified by their dominant macrophyte species: 1) *Eleocharis* spp. (rush) marsh; 2) *Cladium jamaicense* (sawgrass) marsh; and 3) *Typha domingensis* (cattail) marsh. While many marshes contain mixtures of these three species (and other, less common ones), different nutrient and hydro-period tolerances between these three species favors marshes dominated by either *Eleocharis cellulosa*, *Cladium jamaicense*, or *Typha domingensis* (Rejmankova et al. 1995, 1996b). Forested wetlands in northern Belize have been less rigorously studied, but include two main types: 1) gallery forests along the Hondo and New Rivers and 2) swamp forests in the seasonally inundated karst depressions. The seasonally flooded forests typically support stands of evergreen and deciduous trees and palms 4-20 m in height (e.g., Wright et al. 1959).

The malaria vector *Anopheles albimanus* breeds in cyanobacterial mats that are common in the *Eleocharis* spp. marsh (Rejmankova et al. 1993, 1996a). The malaria vector *Anopheles vestitipennis* breeds in flooded forests and even more commonly in marshes with tall, dense macrophyte vegetation, which is most typical of the *Typha domingensis* marsh (Rejmankova et al. 1998). Cyanobacterial mats providing habitat for *Anopheles albimanus* larvae occasionally develop within sparse stands of *Cladium jamaicense*, and especially dense stands of *Cladium jamaicense* can provide breeding habitat for *Anopheles vestitipennis*. Nevertheless, on a regional scale *Cladium jamaicense* marsh is not a major *Anopheles* mosquito producer. Given these associations between *Anopheles* breeding and *Eleocharis* spp. marsh, *Typha domingensis* marsh,

and flooded forests, our satellite remote sensing efforts focused on these three wetland types. Two other malaria vectors in Belize, *Anopheles darlingi* and *Anopheles pseudopunctipennis*, breed mostly in rivers and streams (Manguin et al. 1996; Roberts et al. 1996; Roberts et al. 2002), are rare in marshes and flooded forests, and are not a part of this study.

In this study we address two malaria control issues in northern Belize with the analysis of satellite imagery. The first is to use satellite imagery to map *Anopheles* mosquito breeding sites. The second is to use satellite imagery to determine the degree to which agriculture impacts wetlands where *Anopheles* mosquitoes breed. Our specific objectives are: 1) Map land cover and *Anopheles* larval habitats; and 2) Test the hypothesis that phosphorus runoff from agricultural lands is causing an expansion of *Typha domingensis* marsh. Several studies in the Florida Everglades have demonstrated that wastewater from agriculture can cause the expansion of *Typha domingensis* (e.g., Davis 1991; Newman et al. 1996; DeBusk et al. 2001; Childers et al. 2003), and satellite imagery has been extremely useful in documenting this change (Jensen et al. 1995; Wu et al. 1997). In this study we demonstrate: 1) that the breeding sites of *Anopheles* mosquitoes can be mapped in northern Belize with satellite imagery; and 2) that there is a weak but statistically significant correlation between the amount of *Typha domingensis* in a marsh and the amount of agricultural land in the adjacent drainage. These results suggest that runoff from agricultural fields is increasing malaria risk in northern Belize, and in other regions where *Anopheles vestitipennis* is a major malaria vector.

## **METHODS**

### **Satellite Image Cluster Analyses**

Our analysis of wetlands and adjacent land use is based on a land cover classification derived from a cluster analysis of SPOT and Radarsat satellite imagery. We acquired a multispectral SPOT image (green, red, near infrared, and shortwave infrared bands) from March 2000 (re-sampled to 12.5 m pixels to match the Radarsat pixel size) and a series of Radarsat C-band (5.6 cm wavelength) horizontal like-polarized (HH) synthetic aperture radar images from December 1999, January 2000, February 2000, and July 2000. We used a hand-held GPS to obtain geographic coordinates of road intersections, which we then used to georeference the SPOT image to a UTM map base. The Radarsat images were next coregistered to the SPOT image using tie points from prominent landscape features recognizable in both the SPOT and Radarsat images. We then used two passes of a 3 x 3 pixel moving window median filter to reduce the speckle noise in the Radarsat image (e.g. Gagnon and Jouan 1997). The combined 4-band SPOT and 4-date Radarsat image data set was run through multiple iterations of the ISOCCLASS clustering algorithm to produce 75 clusters (Tou and Gonzalez 1974). These 75 clusters were next grouped into 9 classes using the cluster dendrogram, selecting the most distinct groupings. We compared the image-based map with field observations (with GPS coordinates) of land cover to assign each class into one of nine provisional land cover types: water, low marsh, medium marsh, high marsh, forest, agricultural type 1 (Ag1) agricultural type 2 (Ag2), agricultural type 3 (Ag3), and urban/bare ground. The process permitted a quick appraisal of the land cover types that could be identified, and the degree to which the cluster analysis separated known wetland and land use types. We found that overall the class groupings matched well with known land cover types, but there was notable confusion between some of the wetland and agriculture classes. To address this problem, we re-ran the ISOCCLASS cluster analysis (with 32 clusters) for the areas that corresponded to the four provisional wetland classes (water, low marsh, medium

marsh, high marsh) and one agricultural class (Ag3) where most of the apparent confusion occurred. We compared the results of this focused cluster analysis with the field observations and found that the confusion between wetland and agriculture was reduced, but not eliminated.

### **Radar Detection of Seasonal Flooding**

Comparison of the wetland land cover classes with our field observations indicates that the *Eleocharis* spp. marsh correlates well with our low marsh class. Nevertheless, the cluster analysis did not separate the *Typha domingensis* marsh from other high marsh types, or the flooded forests from other forest types. To address this problem we performed a more detailed analysis of the Radarsat imagery. Our previous radar research noted that flooded *Typha domingensis* marshes typically produce very high C-band HH polarized backscatter due to the double reflection of the radar signal off the vertical stem and water surface (Pope et al. 1997). Examination of the December 2000 Radarsat image revealed that our field observations of *Typha domingensis* marshes matched well with bright (high backscatter) patches in the image. Studies of *Typha domingensis* marshes in Yucatan determined that these marshes produced a mean backscatter of  $>0.7$  dB when flooded (Pope et al. 1997), which is higher than any other natural vegetation type in the region (Pope et al. 2001). Therefore, we performed a threshold operation on the December 2000 Radarsat image to identify all pixel values  $>0.7$  dB, and classified these pixels as of *Typha domingensis* marsh.

Previous radar studies of C-band HH polarized backscatter from flooded forests in Yucatan noted a double reflection of the radar signal off the vertical trunks and water surface, similar to that found in the *Typha domingensis* marshes, but the effect was subdued due to the absorption of the C-band signal by the upper forest canopy (Pope et al. 2001). A backscatter increase of 1-3 dB occurs between dry season non-flooded and wet season flooded forests, with

the larger increase coming from forests with continuous flooding (Pope et al. 2001). We extracted backscatter statistics from the non-flooded upland forest in the Radarsat images (several dates) and found that it is relatively constant at  $-7.9 \pm 0.2$  dB; hence a flooded forest would be expected to have a backscatter of  $\sim -5$  dB. Unfortunately the Radarsat imagery we used in the cluster analysis contained only images from the end (December) and beginning (July) of the wet season, periods when forest flooding is not extensive. Therefore, we obtained another Radarsat image from October 2000 that was acquired only a few days after Hurricane Keith crossed northern Belize and forest flooding was at its seasonal maximum. This image was coregistered and filtered as with the other Radarsat images. We did not use this image in our cluster analysis because it does not cover the entire study area, but it is the only image suitable for identifying flooded forests. We used the forest land cover type produced from the cluster analysis described above to extract a segment of the October 2000 Radarsat image that corresponded to forest. A threshold function was then applied to classify pixels with values  $> -5$  dB as flooded forest. This segmentation was necessary because, unlike the *Typha domingensis* marsh, the backscatter from flooded forests is not unique, as many non-forest vegetation types produce backscatter values  $> -5$  dB. A single pass of a 3 x 3 modal filter was performed on the binary threshold image (0 = non-flooded, 1 = flooded) to reduce the blotchy appearance of the flooded forest in the image. This blotchy appearance may be due to: 1) radar speckle, which is a form of noise typical of coherent imaging systems such as radar; 2) uneven penetration of the forest canopy by the C-band radar; 3) patchy flooding in the forests; or 4) a combination of these three factors.

### **Classification Accuracy Assessment**

We assessed the accuracy of our land cover classification for each land cover type of interest to our malaria research by comparing the classification results with field observations (these observations were made independently from the observations used in the initial grouping of ISOCLASS clusters). Our field observations were made in 2002, thus changes in land use and marsh cover may have occurred since the images were acquired in 2000, but on a regional basis these changes are minor. GPS coordinates were acquired in the field for 6 sugar cane, 6 annual crop, 6 pasture, 6 forest, 6 flooded forest, and 14 marsh test sites, each >1.5 ha. in size. The marsh sites chosen were large tracts and encompassed several marsh types. The flooded forest sites were not flooded at the time of the field selection, but were known to flood each wet season based on earlier observations and the distinctive type of swamp or gallery forest vegetation. A similar approach was applied to the selection of 13 *Eleocharis* spp. marsh sites and 77 *Typha domingensis* marshes sites, although due to the restricted size of these marshes, smaller sites were chosen (0.14 ha for the *Eleocharis* spp. marsh and >0.6 ha. for the *Typha domingensis*). The test sites were then plotted on the classified image and the percent of each class in the site was calculated.

### **Field Transect Analysis**

Using the SPOT-Radarsat classification to locate marshes, field teams selected 40 test sites in Belize for transects and made extensive measurements of vegetation, water, and soil parameters along each transect (S. Johnson and E. Rejmankova, unpublished). Twenty of the field transects were selected in "impacted" marshes with agricultural fields (mostly sugar cane) adjacent to the marsh and 20 transects were selected in "unimpacted" marshes surrounded by forest. All marshes contained at least some *Typha domingensis*. Transects extended 100 m into the marsh

measured perpendicular from the edge of the marsh, and 100 meters in the opposite direction into the adjacent upland. GPS points were taken for the starting point and ending points at the marsh edge for each transect. In some transects a transitional zone (up to 72 m wide) representing a broad ecotone between the perennially flooded marsh and upland was apparent in the field. In these cases, the starting points for the marsh and upland transect were offset by the width of this transition zone.

Transect endpoints, measured by GPS in the field, were imported into ArcGIS (Environmental Systems Research Institute, Inc., [www.esri.com](http://www.esri.com)). Twenty five-meter buffer zones were created around the transects to form sampling boxes of 50 by 100 meters into the marsh, and 50 by 100 meters into the adjacent upland (where present, the transition zone noted above was omitted from the sample) (Fig. 4a). The buffer zones were exported to Geomatica (PCI Geomatics, [www.pcigeomatics.com](http://www.pcigeomatics.com)) and a program was used to count the number of *Typha domingensis* marsh pixels in each marsh buffer zone and the number of forest, agricultural and urban pixels in each upland buffer zone. Linear correlations (Pearson's correlation) were calculated between the amount of *Typha domingensis* marsh in the marsh transect and the amount of forest and agricultural land in the upland transect.

### GIS Buffer Analyses

We expanded our analysis of marshes and adjacent land use by using GIS buffering techniques to examine relationships between *Typha domingensis* marsh and land use on a regional scale. We created buffers around villages and around marshes. To examine the influence of land use on larval habitats within the vicinity of villages, we created 3-kilometer buffer zones around 52 village center points (Fig. 1) and measured the amount of land cover within each buffer zone. A

3-kilometer radius was selected to allow for the village size plus an approximate 2-kilometer flight range of the mosquito. Each buffer zone thus represents an approximation of the area that produces mosquitoes biting within that village.

In order to create buffer zones around marshes, the marshes on the classification (a raster format) had to be converted to a vector format. The land cover classification map (raster image in Fig. 2) was processed to create an image with only two values; a value of zero represented marsh (all types), and 255 represented all non-marsh pixels (Fig. 3). This image contained too many marshes to convert to a vector format, and included many very small (one or two pixel) marshes that we suspected were misclassified. To remove the small marshes, a 7 by 7 mode filter was used on the image (Fig. 3b). After filtering the image, we were able to convert the image to vector format (Fig. 3c). Next we displayed the vector marsh image over a multispectral IKONOS image, which we acquired for the central part of our study area. The IKONOS image was used to edit the SPOT-Radarsat classification and a number of small marshes that appear to be agricultural fields were removed from the classification. The high resolution (4 meter pixels) of the IKONOS image made it possible to distinguish between agricultural fields and marshes using photointerpretation techniques (texture, pattern, adjacent land cover type). The edited marsh image contained 112 marshes composed of  $\geq 5$  pixels ( $\geq 0.08$  ha.). Marshes boundaries were then buffered with a 25-m-wide buffer inside the marsh margin and a 100-m-wide buffer outside the marsh margin (Fig. 4b).

The amount of each land cover type within the village and marsh buffer zones was calculated using the ArcGIS and Geomatica programs. Linear correlations (Pearson's correlation) were calculated between the amount of *Typha domingensis* marsh in the buffer inside the marsh and the amount of forest and agricultural land in the buffer outside the marsh. Linear correlations

(Pearson's correlation) were also calculated between the amount of *Typha domingensis* marsh and each land cover type within the village buffers.

## RESULTS

### Land Cover Map

Results of the cluster analyses and the focused Radarsat analyses of flooded *Typha domingensis* marshes and forests were combined into a single land cover map (Fig. 2). The results of the classification accuracy assessment are presented in Table 1. Shown in Table 1 are the percent of the corresponding land cover class found in each test site and the Kappa statistic, which is a measure of the correspondence adjusted for randomness (Congalton and Green, 1999). This assessment reveals the following associations. The Ag3 class correlated with 76% of the area identified as sugar cane, although 14% of the annual crop, 21% of the pasture, and 22% of the *Eleocharis* spp. marsh also correlated with Ag3. Therefore, the Ag3 class reasonably represents sugar cane fields, but there remains some confusion with other agricultural lands and the *Eleocharis* spp. marsh. The small (6%) of forest in the sugar cane sites is probably not misclassified and reflects trees along the margins of the sugar cane fields. The only significant occurrence of the Ag1 class in our tests sites was in the sugar cane fields (12%), thus Ag1 can be considered a variant of sugar cane. Nevertheless, examination of the classification map (Fig. 2) reveals large areas classified as Ag1 in the southern part of the study area that are pine savanna. The Ag2 class correlated with 82% of the annual crop, 77% of the pasture, and 3% of the sugar cane. Thus, our classification did not distinguish between annual crops and pasture, but if these two are combined into one land cover type (crops/pasture), there is only minimal confusion with other types. The forest class accurately represents forest, but there is considerable overlap

between the forest and flooded forest classes. Our accuracy assessment of all marshes combined demonstrates that there is little confusion (~3%) between this broad category and other non-marsh land cover types. The *Eleocharis* spp. marsh correlates with our low marsh class (55%).

### **Associations of *Anopheles* Larval Habitat and Land Use Patterns**

The linear correlation (Pearson's Correlation) between the amount of *Typha domingensis* marsh and land use are presented in Table 2. All three analyses (transect marsh buffer, village buffer) show the same trend of weak but significant negative correlations between forest and *Typha domingensis* marsh, compared to weak but positive correlations between *Typha domingensis* marsh and sugar cane or annual crop/pasture. In general, the strongest correlations were found in the marsh buffer analysis when only marshes with *Typha domingensis* were included, and for the association of *Typha domingensis* marsh and sugar cane.

### **DISCUSSION**

Our research demonstrates that *Anopheles* mosquito breeding habitats and land cover can be mapped in northern Belize with a combination of dry season SPOT multispectral and Radarsat multitemporal satellite imagery. This result adds to a growing number of recent studies that demonstrate the potential of satellite imagery in malaria assessments (e.g., Rogers et al. 2002). In general, classification accuracies with Kappa statistics >80% are considered good, 40-80% moderate, and <40% poor (Congalton 1996). The best result for the habitat mapping is for the *Typha domingensis* marsh (Kappa = 93%), which is a primary larval habitat for *Anopheles vestitipennis*. The two problematic larval habitats in our analysis, the *Anopheles albimanus* larval habitat (*Eleocharis* spp. Marsh, Kappa = 51%) and the other *Anopheles vestitipennis* habitat

(flooded forest, Kappa = 27%), were not evaluated well by our accuracy assessment methods because of their heterogeneity. Field studies at the 13 *Eleocharis* spp. marsh test sites recorded only ~40% cover of *Eleocharis cellulosa* and associated algal mats. The remaining 60% was mostly open water and minor amounts of *Cladium jamaicense* and *Typha domingensis*. Our classification of the *Eleocharis* spp. marsh test sites (Table 1) found an average of 6% water, 14% medium marsh, 2% high marsh, and 2% *Typha domingensis* (the medium and high marsh types represent mixtures of *Cladium jamaicense*, *Typha domingensis*, and *Eleocharis* spp.). Given this heterogeneity, our classification accuracy of the *Eleocharis* spp. marsh may be >70%. The 34% correspondence between our flooded forest test sites and flooded forest class is difficult to assess. As noted above, the radar technique for identifying flooded forests produced a blotchy pattern that may in part be an artifact of the technique, but probably also reflects patchy flooding. The latter possibility could not be evaluated directly, since we have no field observations from the date of the Radarsat data. Nevertheless, our wet season observations in other years consistently found that these forests were <50% flooded. If we assume that <50% of the forests in the tests sites were flooded, then our classification accuracy for this class increases to >68%.

Excellent classification results were obtained for the forest (Kappa = 99%) and moderate to good results were obtained for sugar cane (Kappa = 74%) and our combined pasture/crop class (Kappa = 78%). Note also that in our marsh buffer analysis we used an IKONOS image to edit the sugar cane and pasture/crop classes to exclude small erroneous patches of marsh, thus increasing the accuracy of these classes in that specific analysis. The good classification results for land use, coupled with the excellent results for *Typha domingensis* marsh noted above, give confidence to our assessment of the associations between *Typha domingensis* marsh and land use based on satellite imagery. The correlation analyses presented in Table 2 clearly demonstrate

that *Typha domingensis* marsh is more abundant in marshes bordered by agricultural lands than in marshes bordered by forest. The most consistent results are for a positive correlation between *Typha domingensis* marsh and sugar cane. We propose that this association is the result of nutrient (primarily phosphorus) laden runoff from agricultural fields into adjacent marshes. Previous research in northern Belize has demonstrated that *Typha domingensis* is more abundant than other marsh macrophyte species in marshes with higher soil phosphorus (Rejmankova et al. 1996b) and a field transect study found higher phosphorus levels in the marshes adjacent to sugar cane fields (S. Johnson and E. Rejmankova, unpublished).

While several of the correlations in Table 2 are highly significant ( $p \leq 0.01$ ), the  $r$ -values are low, indicating that only ~5-20% of the variance in the distribution of *Typha domingensis* marsh can be explained by larger amounts of agricultural land versus forests in the catchments. Therefore, current land use is not the dominant factor controlling the distribution of *Typha domingensis* in northern Belize. Nevertheless, it is surprising that the village buffer analysis produced marginally significant correlations between *Typha domingensis* marsh and sugar cane ( $r = 0.23$   $p = 0.10$ ), which suggests that this association exists at a regional scale in northern Belize. It is important to note that the best correlations were found in the analyses that included only marshes that contained some *Typha domingensis* (Table 2, transects and marsh buffer with *Typha*). This may reflect the situation where runoff causes *Typha domingensis* expansion where it already exists, but has little influence in marshes that lack *Typha domingensis* to begin with.

Our conclusion that land use in northern Belize is causing an expansion of *Typha domingensis* marsh, a major breeding habitat for *Anopheles vestitipennis*, has important ramifications for malaria risk in the region. Marshes with sparse or mixed stands of *Cladium jamaicense* and *Typha domingensis* (our land cover classes of medium and high marsh) are not favored breeding

sites for *Anopheles* mosquitoes (Rejmankova et al. 1993, 1995, 1996a, 1998). Furthermore, *Anopheles albimanus* is a less potent malaria vector than *Anopheles vestitipennis* (Elliott 1972; Loyola et al. 1993; Achee et al. 2000, Grieco et al. 2002). Therefore, the replacement of *Eleocharis* spp. marsh and other marsh types with *Typha domingensis* marsh is potentially increasing malaria risk in Belize, and the expansion and intensification of agriculture throughout the region where *Anopheles vestitipennis* is a major malaria vector may cause a widespread increase in malaria.

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**Table 1.** Classification accuracy statistics for selected land cover types. Percent (area) of test sites (average of all sites in class) correctly classified and Kappa statistic. Pasture and annual crop combined into a single class for Kappa statistic calculation.

test site	Ag3 (sugar cane)	Ag2 (pasture/ crop)	Ag1	forest	flooded forest	<i>Eleocharis</i> (low marsh)	<i>Typha</i>	water	medium marsh	high marsh	urban bare ground	Kappa x 100
sugar cane	76	3	12	6	0	1	0	0	1	0	0	74
pasture	21	77	0	1	0	0	0	0	0	0	1	--
annual crop	14	82	1	0	0	0	0	0	0	0	2	--
pasture/crop	18	80	0	0	0	0	0	0	0	0	0	78
forest	0	0	0	99	1	0	0	0	0	0	0	99
flooded forest	2	0	0	62	34	0	0	0	1	0	0	27
all marsh	0	0	1	1	0	41	6	3	14	33	1	--
<i>Eleocharis</i>	22	0	0	0	0	55	2	6	14	2	0	51
<i>Typha</i>	0	0	0	0	0	0	94	0	0	0	6	93

**Table 2.** Pearson correlation coefficients (r) and significance (p) for the amount of *Typha domingensis* in a marsh versus the amount of various land cover types in the adjacent upland. Analyses for transect, marsh buffer, and village buffer analyses (see text).

	<i>Typha</i> vs. Forest		<i>Typha</i> vs. pasture/crop		<i>Typha</i> vs. sugar cane		<i>Typha</i> vs. agricultural land	
	r	p	r	p	r	p	r	p
Transect (n=40)	-0.22	0.18	--	--	0.41	<0.01	--	--
Marsh buffer, all (n=112)	-0.14	0.13	0.17	0.07	0.23	0.01	0.25	<0.01
Marsh buffer, with <i>Typha</i> (n=37)	-0.48	<0.01	0.33	0.05	0.35	0.03	0.39	0.02
Village buffer (n=52)	-0.21	0.14	0.05	0.71	0.23	0.10	0.23	0.11

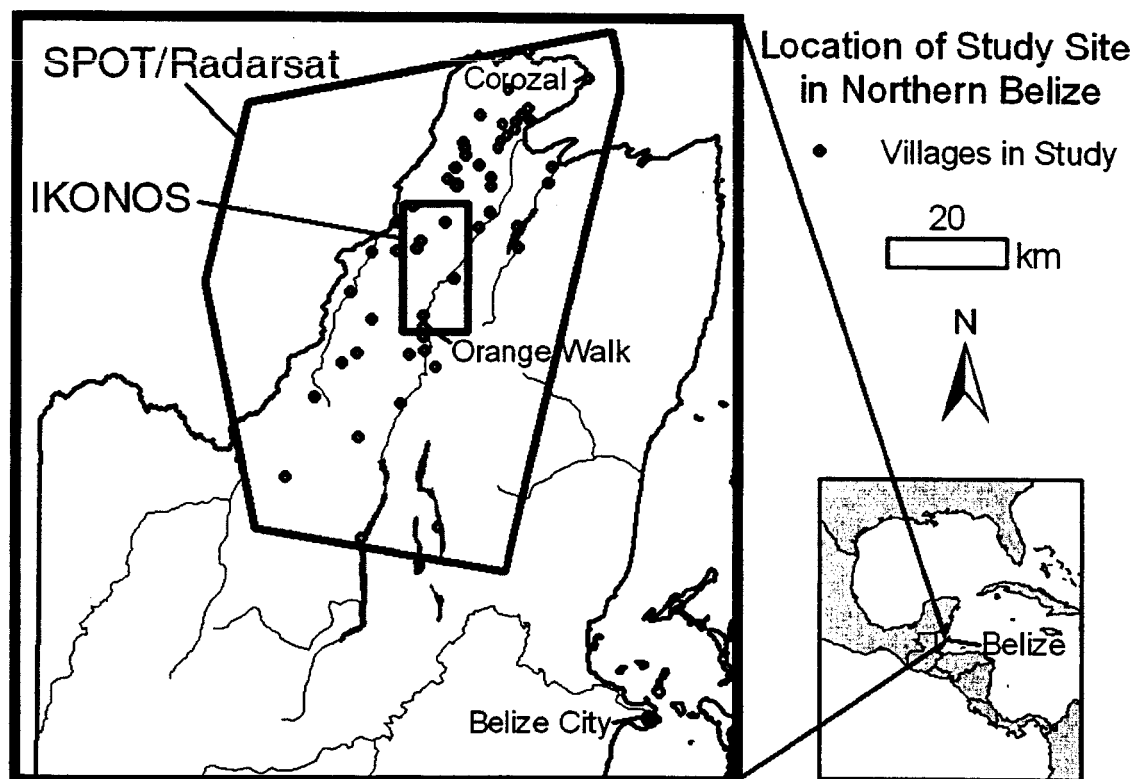
**Figure 1.** Map of northern Belize study area showing major towns, villages, rivers, and satellite image foot prints for the SPOT-Radarsat classification (Figure 2) and the IKONOS image discussed in text.

**Figure 2.** SPOT-Radarsat classification of northern Belize (see Fig.1 for location). Black line shows border of October 2000 Radarsat image used to map flooded forest. Key: 1 = urban/bare ground; 2 = Ag1; 3 = Ag2 (pasture/crop); 4 = Ag3 (sugar cane); 5 = forest; 6 = flooded forest; 7 = *Typha domingensis* marsh; 8 = high marsh; 9 = medium marsh; 10 = low marsh (*Eleocharis* spp. marsh); 11 = water.

**Figure 3.** Steps in processing marsh classification from raster to vector format. (A)

Classification image converted to 2 values: black for marsh and water pixels, white for all other land cover classes. (B) Image filtered using a 7 by 7 mode filter. (C) Image converted to a vector line format and manually edited to remove all island polygons and rivers.

**Figure 4.** Buffer zones around field transects and marshes. (A) Twenty five meter buffer zones around 100 meter marsh transects. Light gray buffer zone samples marsh vegetation, dark gray buffer zone samples upland land cover. See land cover key in Fig. 2. (B) One hundred meter buffers outside and 25 meter buffers inside marsh boundaries. One hundred meter buffers (green) sample the upland vegetation. Twenty five meter buffers (dark blue) sample inside the marsh. Marsh not falling within the twenty five meter buffer zone is shown in light blue.



**Figure 1.**

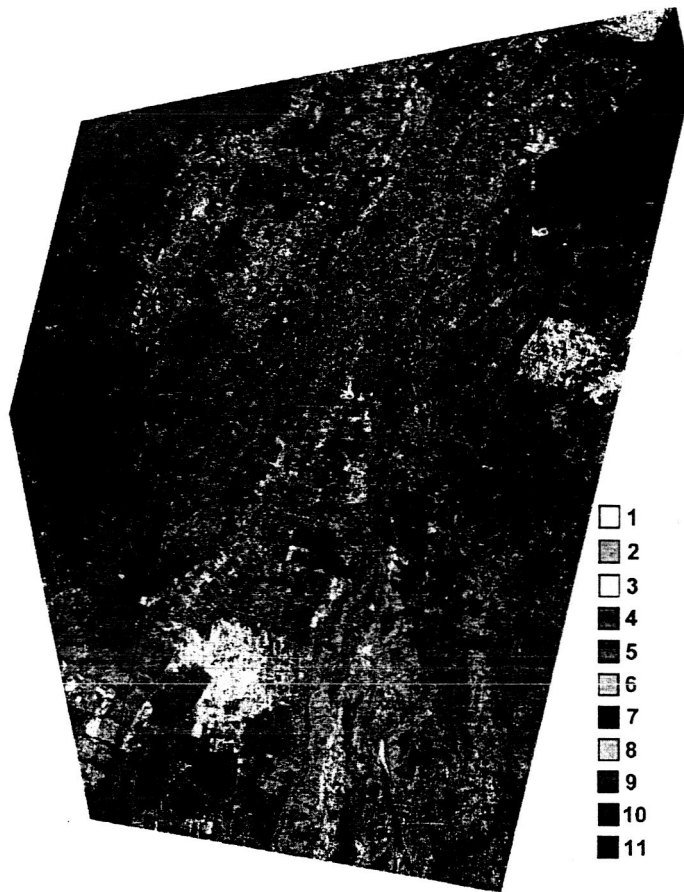


Figure 2.

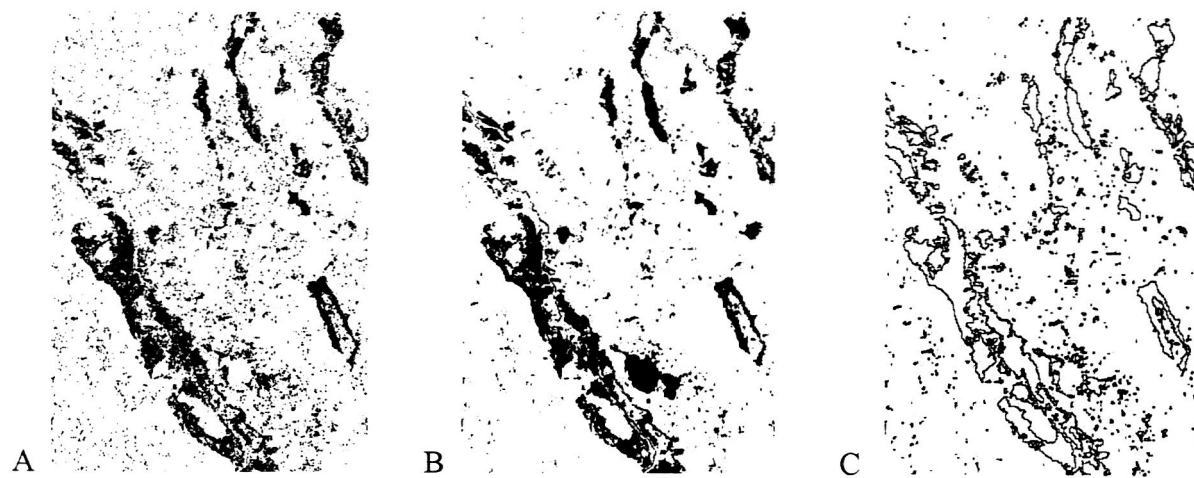


Figure 3.

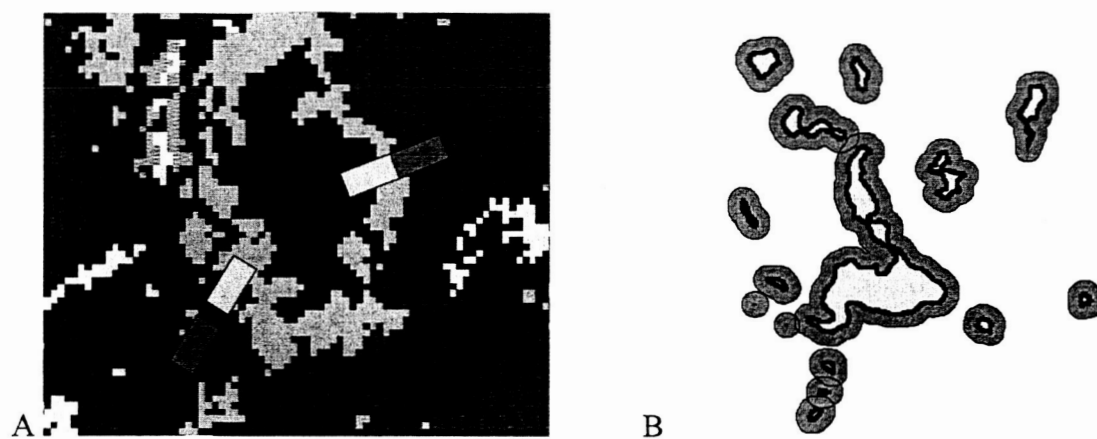


Figure 4.